ENERGETIC SOLAR PARTICLE FLUXES OUT TO 3 AU DURING THE MAY 7, 1978 FLARE EVENT

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Simultaneous solar proton flux measurements on IMP 7 and by the world-wide neutron monitor network during the May 7, 1978 flare event led us to conclude that in the energy range from 50 MeV to 10 GeV: 1) the propagation of the flare particles in the interplanetary magnetic field (IMF) between the sun and the earth was nearly scatter-free; and 2) therefore, the intensity-time (IT) profiles of the solar proton fluxes observed at earth for about one hour after onset represent the solar injection profiles even to energies as low as 50 MeV (Debrunner et al., 1984). Observations of the IMF at Helios A indicate that the IMF was undisturbed between the sun and Helios A at the time of the May 7, 1978 flare event; and, therefore, we infer that the solar particle propagation was also scatter-free from the sun to Helios A. We then made a detailed study of the acceleration and coronal transport of the flare particles and their injection into the IMF using the fine-time resolution data from IMP 7 and Helios A (Lockwood and Debrunner, 1983, 1985). The relative positions of IMP 7 and Helios A spacecraft along with the solar flare location are shown in Fig. 1. The IMF lines are drawn for a solar wind speed V_{SW} = 480 km/s. As an example of the solar particle fluxes observed at IMP 7 and Helios A we show in Fig. 2 the responses of the energy channel with E_{median} $\sim$ 90 MeV. The coronal transport was then analysed by assuming a δ-like acceleration of the protons at the flare site and by using the Reid (1964) and Axford (1965) model of two-dimensional diffusion with losses. Comparing the (IT) profiles from IMP 7 and Helios A, we found that the coronal diffusion coefficient D_S^E [cm^2/s] $\sim 4.4 \cdot 10^{15}$ (E [MeV] $)^{\frac{1}{2}}$ for 20 MeV < E < 500 MeV and that the loss rate $\beta^E \sim (2.9 \pm 0.5)$ hr^{-1} for 90 MeV < E < 500 MeV. To test the validity of the model used and the deduced parameters we then calculated the ratios of the maximum solar proton fluxes at IMP 7 and Helios A for the energy channels E_{median} $\sim$ 90 MeV and $\sim$ 350 MeV. The calculated ratios agree with the observed ones to within a factor of 2 which is good agreement. The constancy of the factor with energy further confirms the results of this analysis.

Here we apply the same model to interpret the solar proton fluxes observed on the Voyager (V) spacecraft, the locations of which are also given in Fig. 1. The solar particle fluxes for the two high energy telescopes (HET) from 70 MeV < E < 500 MeV (E_{median} $\sim$ 107 MeV) at V1 and V2 are combined and shown in Fig. 3. The combination of the data is valid because the counting rates of the four HETs agreed within statistical fluctuations. In Fig. 3 we also show the (IT) profile (shaded area) expected at V according to our model of only coronal transport without IMF diffusion. Comparing the onset time and (IT) profile of the theoretical response (no IMF diffusion) with the observed ones it is clear that the propagation of the solar protons was

diffusive beyond the orbit of the earth. In order to include the effects of the IMF diffusion we must determine the extent of the region over which the diffusion took place. We examined the plasma and magnetic field data on Helios A from April 25 to May 7, the Kp data at earth from April 29 to May 10, and magnetic field and solar wind data on V1 and V2 from May 7 to May 17. The shocks and/or disturbed regions found on May 7, 1978, at 0300 UT are indicated in Fig. 4. In this figure we have also shown the IMF lines to Voyager for V_{SW} = 420, 455, and 490 km/s. We infer that the propagation of the solar particles along the IMF lines to Voyager was scatter-free for $r < 1.6$ AU and diffusive for $r \geqslant 1.6$ AU.

To describe the diffusive propagation of the flare protons for $r \geqslant 1.6$ AU we assume as explained in Fig. 5 one-dimensional diffusion along the IMF lines with a constant mean free path λ, an "absorbing" barrier at $x = -2\lambda$, and a δ-like injection of N particles at $x = 0$, $t = 0$. The presence of an "absorbing" barrier at $x = -2\lambda$ is the equivalent physical description of the transition of the flare protons from the undisturbed to the disturbed region. The density of solar particles is then:

$$n(x,t) = \frac{N}{2(\pi Dt)^{1/2}} \left\{ \exp\left(-\frac{x^2}{4Dt}\right) - \exp\left(-\frac{[x+4\lambda]^2}{4Dt}\right)\right\} \quad (1),$$

where $D = \lambda v$, λ = mean free path for scattering and v is the particle velocity. If $x \gg \lambda$, then

$$n(x,t) = \frac{N}{(\pi Dt)^{1/2}} \cdot \frac{x}{vt} \cdot \exp\left(-\frac{x^2}{4Dt}\right) \quad (2),$$

which exhibits the same time dependence as 3-dimensional diffusion. The best fit of equation 2 to the Voyager data is found for $\lambda = 0.04$ AU in the range $1.6 \text{ AU} \leqslant r \leqslant 3.0$ AU. The theoretical data were normalized to the observations at the time of maximum and shown in Fig. 3. The agreement of the onset times and of the (IT) profiles over 3 days is excellent. From the solar transport model and the data from IMP 7 (Lockwood and Debrunner, 1985) we can estimate the value of N and predict the absolute maximum intensity at Voyager if we include the effect of the divergent IMF (Parker, 1963). The ratio of the observed to the predicted maximum fluxes at these large distances from the sun is strongly dependent upon the detailed structure of the IMF and V_{SW}. For example, we find that for V_{SW} = 420, 455 and 490 km/s the ratios are 1.5, 5 and 15 respectively. If we include the effect of solar particles escaping from the diffusive region into the undisturbed region ($r < 1.6$ AU), then being reflected in the undisturbed region, and later returning to the disturbed region, the ratios are reduced by about a factor of 3. The resulting ratios of 0.5, 1.7 and 3 respectively are in very good agreement using such a simple physical model.

We conclude that the coronal transport model developed in Lockwood and Debrunner (1985) and the description assumed here for the IMF diffusive propagation predict the observed solar proton fluxes at Helios A (r = 0.35 AU), near earth, and at the Voyager spacecraft (r = 3 AU) for the May 7, 1978 solar flare event.

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References

Axford, W.F., Planet. Space Sci. 13, 1301, 1965.
Debrunner, H., E. Fluckiger, J.A. Lockwood, and R.E. McGuire, J. Geophys. Res. 89, 769, 1984.
Lockwood, J.A., and H. Debrunner, to be published in J. Geophys. Res. 1985.
Lockwood, J.A., and H. Debrunner, Proc. 18th Int. CRC 4, 185, 1983.
Parker, E.N., Interscience Pub. (J. Wiley & Sons), 1963.
Reid, G.C., J. Geophys. Res. 69, 2659, 1964.

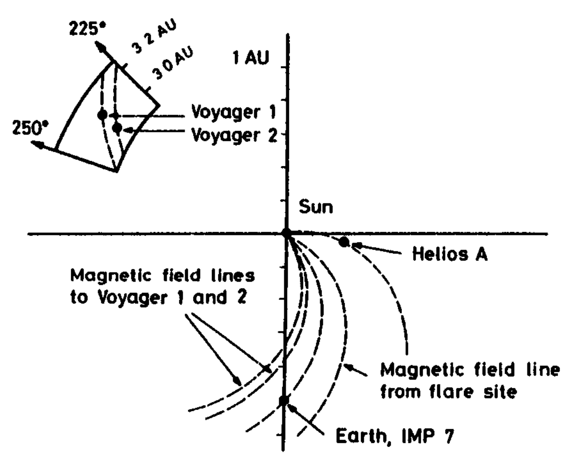

Fig 1 Location of Helios A, the earth, IMP 7, V 1 and V 2 on May 7, 1978.

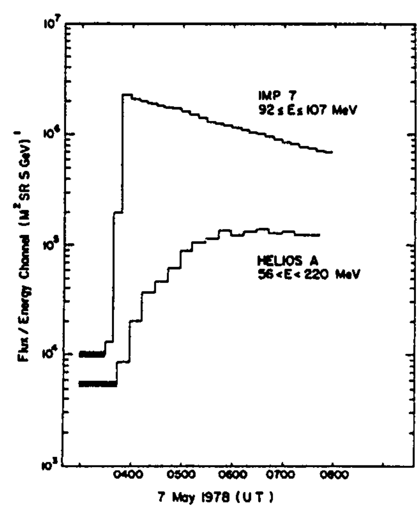

Fig. 2 Solar proton fluxes observed at Helios A and IMP 7 on May 7, 1978 for $E_{median} \sim 90$ MeV

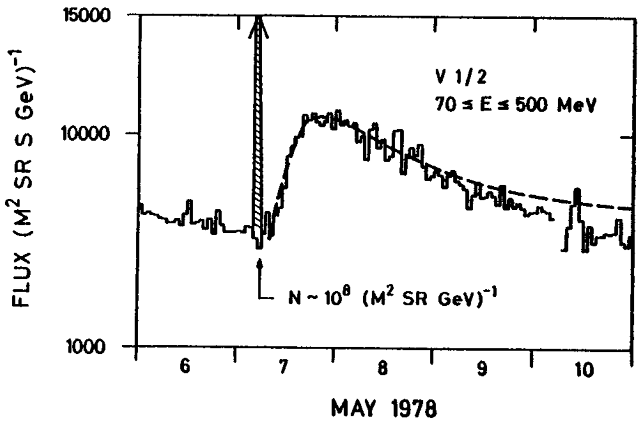

Fig. 3 Solar proton flux at V (—) compared with predicted flux (---) Shaded area is the expected solar proton flux with coronal transport only

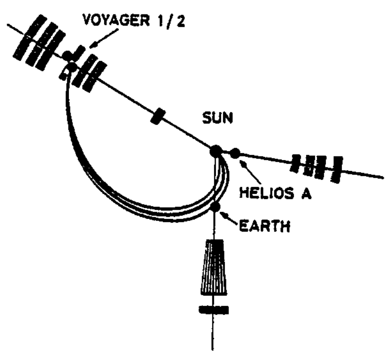

Fig 4 Locations of shocks and/or disturbed regions at 0300 UT on May 7, 1978

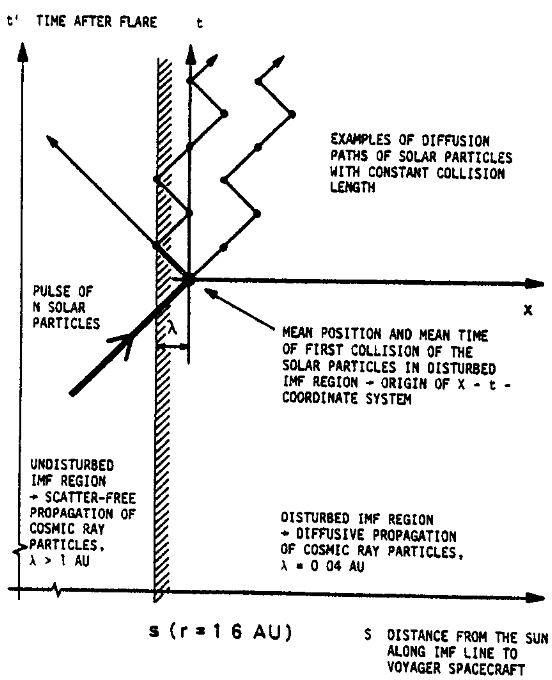

Fig 5 Schematic representation of the assumed model for the IMF diffusion